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This report covers research performed under Grant AFOSR-91-0052. The work consisted of five separate projects: 1) Active Control of Jet Engine Surge; 2) Turbomachinery Vortical Flows in an Adverse Pressure Gradient; 3) Enhanced Mixing Using Embedded Streamwise Vorticity; 4) Rotor-Stator Interaction and Turbomachinery Stall Behavior; and 5) Suction and Blowing Strategies for Fan Noise Reduction.

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Introduction

This report describes progress on the Air Force Research in Aero Propulsion Technology (AFRAPT) Program. The report covers the period September 1, 1993 to March 31, 1995 and consists of short descriptions of the research of each student during this period. The students, their advisors, and the research projects are as follows:

Trainee:	Sean L. Borror (M.S. 6/94)
Advisor:	Professor A.H. Epstein
Project:	Active Control of Surge in an Aircraft Jet Engine
Trainee:	John M. Brookfield (1/2 supported by AFRAPT)
Advisor:	Professor I.A. Waitz/Dr. K.U. Ingard
Project:	Rotor-Stator Interaction Noise Reduction
Trainee:	Martin B. Graf
Advisor:	Professor E.M. Greitzer/Dr. C.S. Tan
Project:	Effects of Rotor-Stator Interaction on Turbomachinery Stall Behavior
Trainee:	Amrit S. Khalsa [Andrew Rothstein] (1/2 supported by AFRAPT)
Advisor:	Professor I.A. Waitz
Project:	Turbomachinery Tip Clearance Vortex Flows
Trainee:	David Tew
Advisor:	Professor I.A. Waitz
Project:	Enhanced Mixing Using Embedded Streamwise Vorticity

Description of the Research

Brief descriptions of the different research projects are given below; detailed descriptions will be given in the M.S. and Ph.D. theses of the graduate student trainees.

Active Control of Surge in an Aircraft Jet Engine Sean L. Borror

The natural and forced hydrodynamic stability of an aircraft gas turbine engine has been investigated analytically and experimentally. A sketch of the engine diffuser is given in Figure 1. This shows the placement of some of the instrumentation; pressure and flow measurements were also made at other locations in the engine (see M.S. thesis of S. Borror, 1994). Time-resolved data gave no evidence of pre-surge one- or two-dimensional oscillations. Measurements of various internal flow processes were found to contain significant frequency content only below 100 Hz. In this frequency range, the spectral content was found to be broadband. The spectral amplitude below 50 Hz was observed to increase roughly 250 ms prior to surge.

Experimental testing of a fluid dynamic actuator designed for use on a Lycoming LTS-101 gas producer revealed that acoustic resonances in the actuator flow path could reduce the level of modulation possible if forced above 200 Hz. Actuation is accomplished by injecting air into the engine's vaned diffuser throats. The effect of steady injection on the compressor characteristic was determined experimentally and found to cause a blockage which reduced the engine inlet flow. The injection also caused a 0.7% loss in total pressure across the diffuser at an operating point near surge while injecting 1.3% of the nominal engine mass flow.

Transfer function estimates between injection mass flow and both combustor and compressor inlet pressure were obtained by unsteadily forcing the engine with the fluid dynamic actuator. Near surge, the engine response to diffuser throat forcing began to roll off at 30 Hz. By 100 Hz, the response was roughly one-tenth that at 30 Hz.

A lumped parameter hydrodynamic stability model was fit to the transfer function estimates obtained from forced response data. Fits to data taken just prior to surge gave an estimate of the engine's natural frequency and damping ratio at 27 Hz and 0.46 respectively.

A nonlinear simulation of a lumped parameter hydrodynamic stability model was found to exhibit the type of abrupt surge behavior observed experimentally. An example of such behavior in a phase plane and in a time history representation is shown in Figure 2. Broadband perturbations to combustor pressure, heat release, and turbine flow were found to elicit a simulated engine response only below forty percent of the engine's Helmholtz frequency.

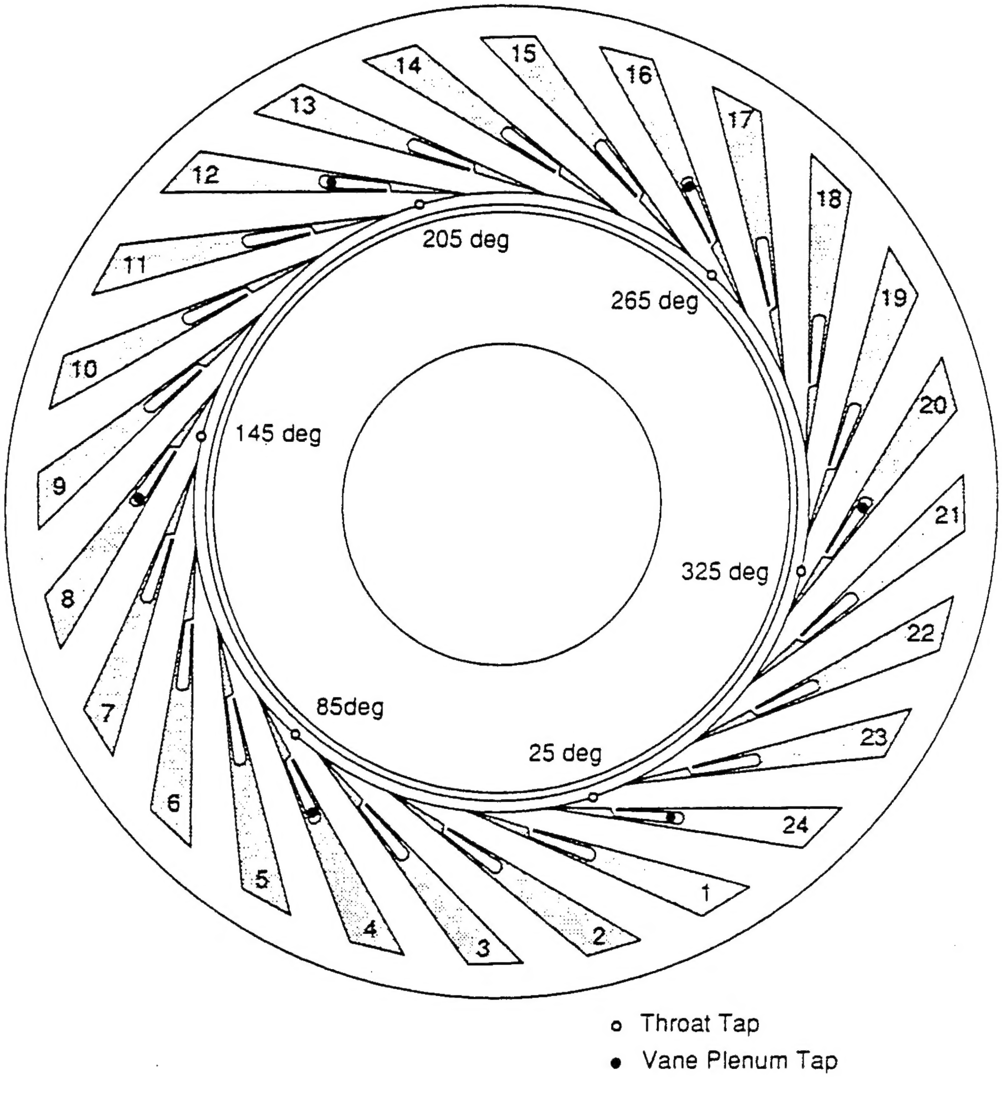

Fig. 1: Instrumented van plenum locations.

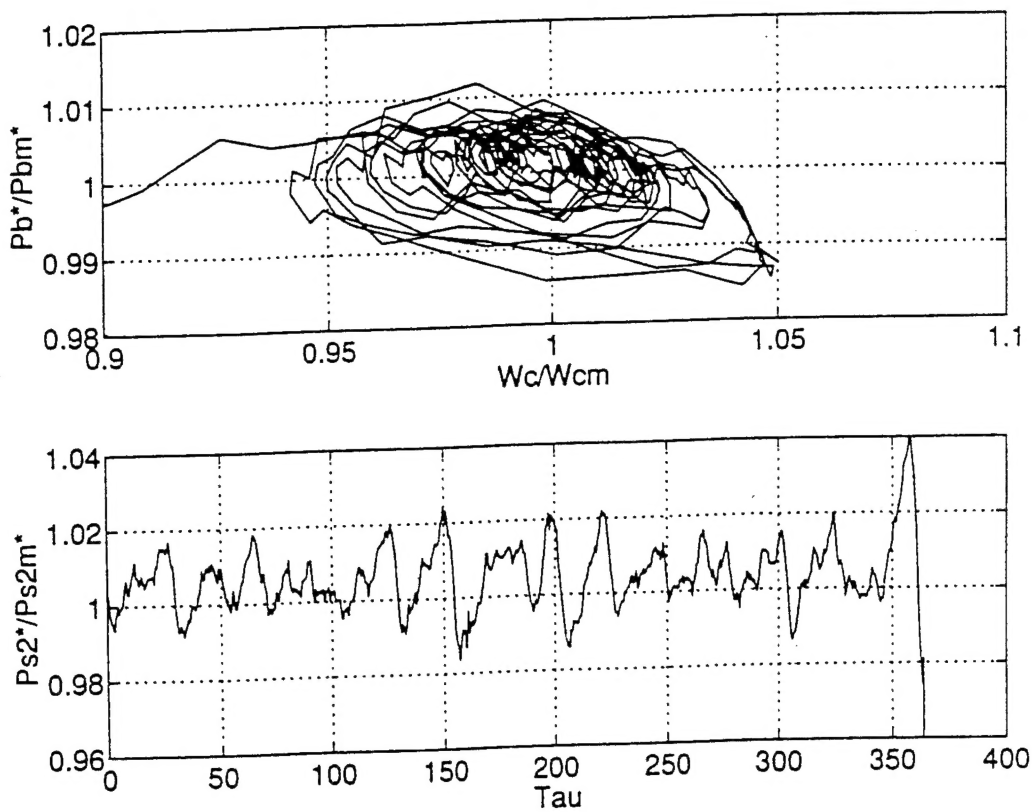

Fig. 2: Example of abrupt surge behavior with combustor perturbations with an rms of 0.2% of combustor mean pressure.

Rotor-Stator Interaction Noise Reduction John M. Brookfield

Radiated noise due to the impingement of rotating fan wakes on the downstream stationary blade row is thought to be the primary source of aircraft engine noise on takeoff and approach. To meet future FAA noise restrictions, new technologies will be required beyond the conventional techniques of increased rotor-stator spacing, reduced velocities, and advantageous blade counts. As an example, one new technique being touted is active control. However, since the use of actively controlled anti-noise has little hope of controlling broad band noise, which is as important as tonal noise, this method can only achieve approximately 3 dB noise reduction.

To control both tonal and broad band noise radiated from the rotor-stator interaction, one must affect both the steady and unsteady flow field components downstream of the fan. To accomplish this goal, a study has been initiated on the use of fan blade boundary layer suction and trailing edge blowing to reduce the magnitude of the steady wake deficit, as well as the unsteadiness in the wakes. These reductions will lead directly to reductions in the unsteady loading of the stator blades and thus reduced radiated noise. Trailing edge blowing experiments on a flat plate at Lehigh University have shown that substantial reduction of both steady wake deficit and wake unsteadiness are possible. It is envisioned, and partially demonstrated in computations, that boundary layer suction will have similar effects, depending on the geometry of the fan blade.

To examine the effects of boundary layer suction and trailing edge blowing on the wake behind a loaded airfoil, computations and cascade experiments are currently being performed. Coupling of this data with unsteady computations of stator loading and with a noise radiation code (written by Ingard) will allow the design of suction and blowing strategies on a current technology high-bypass turbofan.

The implementation of these strategies requires the ability to design hollow fan blades for the addition or removal of fluid, including calculation of the flow internal to the blade. Due to the blade rotation, the internal flow field is more complicated than in a stationary tube. Since the desired suction or blowing on the blade will have a specific spanwise distribution for maximum noise reduction, several internal passages will be required, each servicing one section of the blade

span. Computer code has been written to design these passages.

Although the blade passages have not yet been designed in detail, the method of blade manufacture has been determined. Because of the relative thinness of fan blades, the blades will initially be made as solid according to the original design. The blades to perform suction or blowing will then have passages milled into them from either the suction or pressure surface (depending on whether suction of blowing is to be performed) with a sheet welded over the passages to reform the blade surface.

The rig tests will be carried out in the Blowdown Compressor facility in the Gas Turbine Lab at MIT. This facility uses a Freon/Argon gas mixture, and thus has approximately half the blade stress level as a comparable air facility, allowing for the hollow blades to be built more easily. The modification of the facility and all the parts required to test the solid blade set have been designed (see attached layout drawing) and will be fabricated within the next six months. This testing will give a baseline for the noise reduction studies to be carried out later, as well as allow examination of unsteadiness and three dimensionality. Unsteady loading of the stator blades will be determined by measuring the unsteady pressures on the stator surfaces using a translating stator blade instrumented at one spanwise position with chordwise spaced pressure transducers. Microphones will also be used in the duct to obtain a qualitative measure of the duct acoustics. These initial experiments, plus the computations, cascade experiments, and noise radiation codes, will provide the necessary information for the design of wake management strategies for reduction of rotor-stator interaction noise which will then be tested.

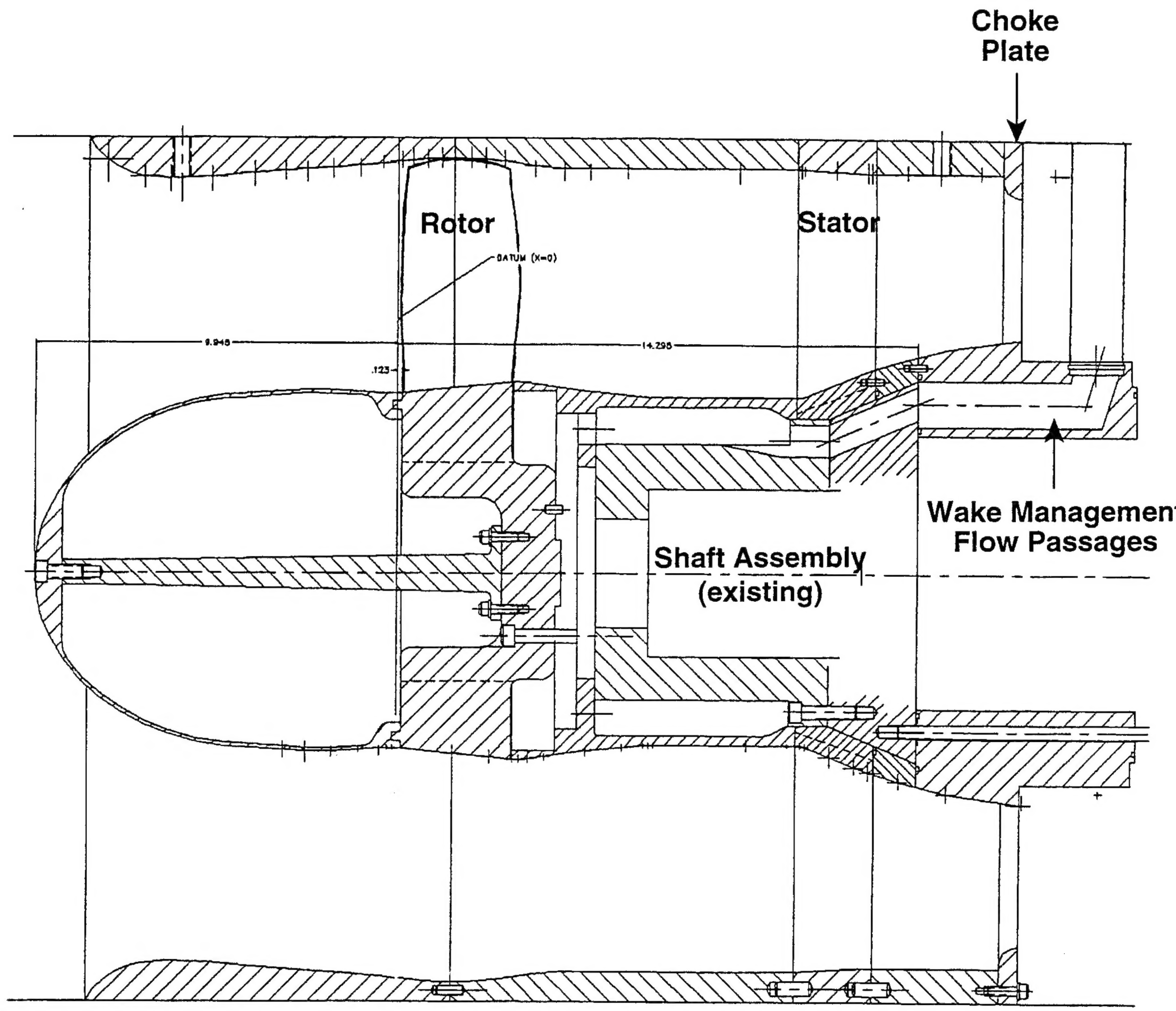

Fig. 3: Layout drawing of noise reduction fan in the Blowdown Compressor at MIT.

<u>Effects of Rotor-Stator Interaction on Turbomachinery Stall Behavior</u> Martin B. Graf

Work has been initiated in the area of tip clearance flow and its effects on compressor stability. The two problems to be addressed during the research program are: (1) Effects of Asymmetric Tip Clearance on Compressor Stability, and (2) Investigation of Downstream Stator Effects on Upstream Rotor Stall. Both of these projects are computational but may involve comparisons with experimental data.

Research on the first topic was completed during the past year. A compressor stability analysis code was written based on an extension of the model of Hynes and Greitzer [1]. Casing asymmetry was modeled assuming that the tip clearance at each circumferential position was determined by the shape of the casing; this results in a varying compressor pumping characteristic around the circumference. This envelope represents the region of performance of the compressor with non-uniform clearance. A typical example is shown in Figure 4. Families of characteristics were generated based on the size of the asymmetry and such items as peak curvature and peak pressure rise. The characteristics and the corresponding casing variation were then input to the code, which computes the steady background flow and performs a linearized stability analysis of the system.

A notable result was the change in stability onset as a function of clearance asymmetry amplitude and characteristic family peak alignment. Figure 5 shows this for a three-stage compressor with a cosine shaped casing variation having the specified nominal pressure rise characteristic. This result illustrates that casing distortion has a substantial effect on stability with the peak pressure rise depending roughly on the maximum tip clearance. Further, the loss in stability was worse than one would find based on the average clearance.

Throughout the investigation, the effect of several other parameters in conjunction with clearance asymmetry was examined. The details of the study have been written up in an internal report, but some other conclusions are repeated here: (1) Tip clearance asymmetry due to casing distortion can be modeled using a parallel compressor concept with each circumferential location operating on a different pressure rise characteristic. (2) Increasing the magnitude of the clearance

asymmetry can decrease the stalling pressure rise and increase the stalling flow coefficient. The loss in pressure rise capability scales roughly with the maximum of the clearance asymmetry. (3) Distortions generated by tip clearance asymmetry have a rich harmonic content and therefore do not satisfy the integrated mean slope criteria. (4) Compressors which produce characteristics that are steep, have high peak pressure rise, narrow map width, and sharp drop in pressure rise after the peak are more sensitive to clearance asymmetry than those with flatter characteristics. (5) Clearance non-uniformity with wavelength on the order of the circumference produce the greatest loss in stall margin. (6) For a given compressor, sensitivity to clearance asymmetry is a strong function of *B*-parameter.

The second topic to be addressed during the research program will involve a computational fluid dynamic (CFD) study of the effect of blade row interaction on rotor stall. In September 1994, a detailed proposal for this investigation was sent to Pratt & Whitney (East Hartford) so that their computational resources could be utilized. The simulations required are three-dimensional steady and unsteady Navier-Stokes computations of a rotor alone and a rotor-stator combination. Design and near stall points will be examined with an emphasis on those effects associated with coupling of the downstream stator pressure field to the upstream rotor endwall flow. Work on this topic should begin at Pratt & Whitney before the end of 1994.

Reference

1. Hynes, T. P., Greitzer, E. M., "A Method for Assessing Effects of Inlet Flow Distortion on Compressor Stability," ASME *J. Turbomachinery*, vol. 109, 1987, pp. 371-379.

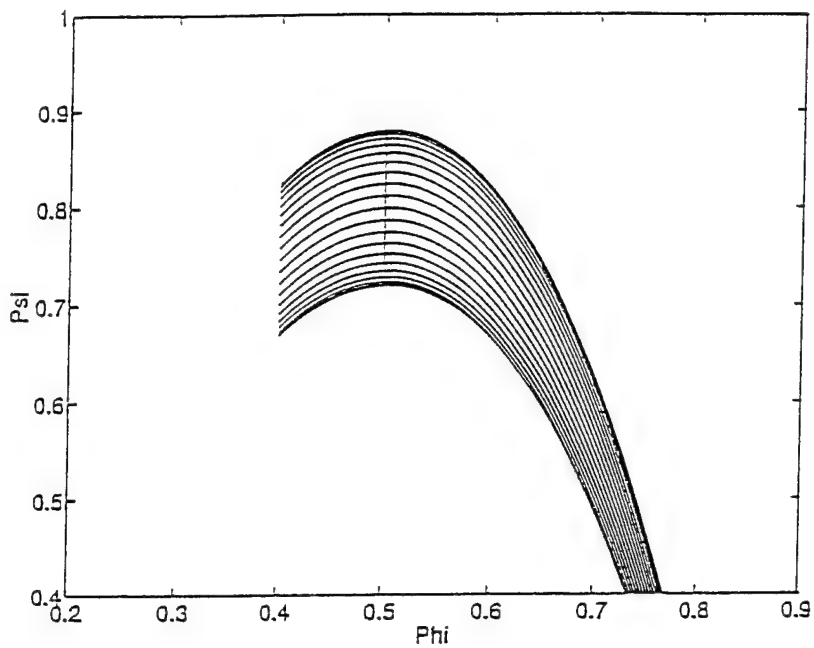

Fig. 4: Three-stage compressor characteristic family for 2% clearance asymmetry with peaks aligned.

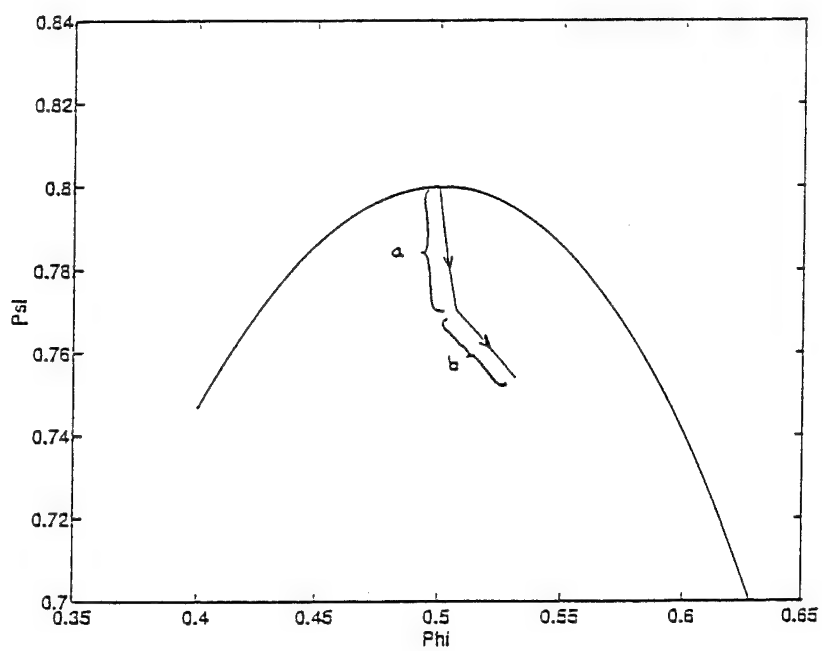

Fig. 5: Locus of neutral stability point movement for cosine clearance variation;
a = change in asymmetry from 0 to 2% clearance/chord, characteristic peaks aligned,
b = characteristic family peak shift from aligned to a 45 degree line at 2% asymmetry.

<u>Turbomachinery Tip Clearance Vortex Flows</u> Amrit Singh Khalsa

This project addresses the fundamental fluid mechanics of compressor tip clearance vortices, in particular, detailed mechanisms of tip clearance flow blockage. The aim is not only to develop prediction methods for endwall blockage but also to suggest possible control or alleviation schemes.

This research is based on abstracting the basic fluid mechanic features of the actual problem, i.e. studying a model of the flow rather then the actual flow which is difficult to interrogate in detail. A curving, diffusing, wind tunnel test section with a slot jet has been designed to capture the most important parameters affecting the tip clearance flow blockage; namely the pressure field in which the leakage jet is immersed, the flow leakage angle and flow rate, and the velocity ratio between the jet and the passage flow. This test section has been built and initial measurements made. A schematic of the tunnel test section is shown in Figure 6. The primary diagnostic is a seven-hole probe. Scans with this probe give the three velocity components and the static pressure at the equivalent to a rotor trailing edge plane.

Complementing these wind tunnel experiments, computational simulations of compressor blade rows and wind tunnel geometry, as well as rotating rig tests (at the Whittle Laboratory, Cambridge University, in Cambridge, England) have been performed. From each of these experiments the relationships between detailed flow structures, blade and passage geometries, and the global, design-oriented parameter of tip clearance-related blockage will be examined.

Tests in the wind tunnel have begun. These will examine the effects of blade loading, pressure rise, clearance leakage flow, injection angle, and jet-to-passage velocity ratio, on clearance-related blockage and loss. The computational experiments offer additional ability to study the flow features in detail, and tests in a rotating compressor rig will connect the results to realistic geometries.

During this year the design and construction of the wind tunnel test section was completed, and data at two leakage angles and five values of pressure rise have been taken. A number of computational simulations have been run. Rotating rig tests were carried out at two staggers, two

clearance heights, and five flow coefficients. From each of these sets of data, clearance-related blockage will be calculated to identify the most influential fluid dynamic trend. The coming year will be focused on distilling a unifying model of tip clearance-related blockage, with the emphasis on developing a practical predictive method and on suggesting possible alleviation schemes. The flexibility of the wind tunnel model will allow some features of casing treatments to be studied, with the goal of extending stable operating range and reducing the efficiency penalty caused by current casing treatments.

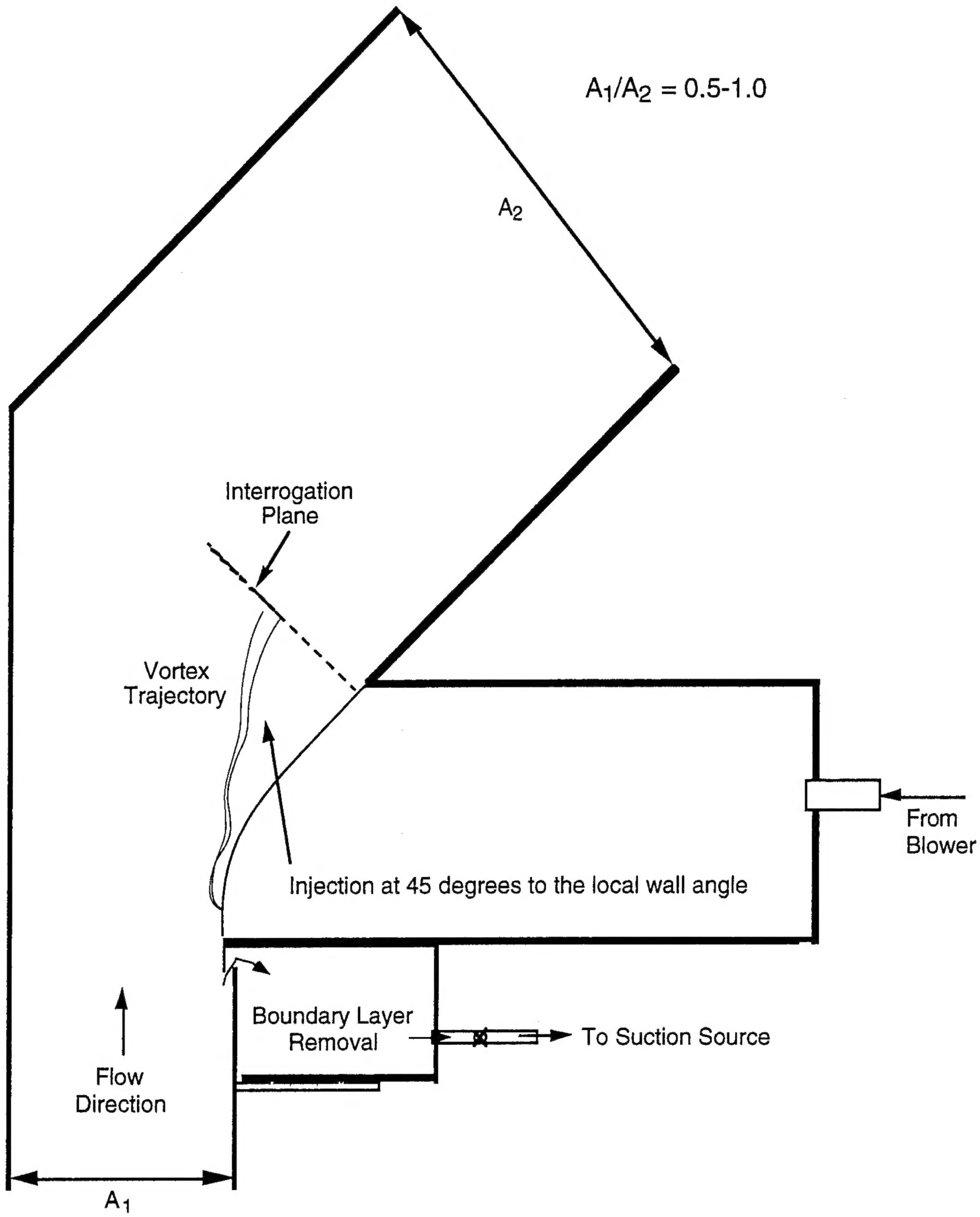

Fig. 6: Wind tunnel test section schematic.

Enhanced Mixing Using Embedded Streamwise Vorticity Dave Tew

This project addresses the influence of compressibility on the effectiveness of mixing enhancement due to embedded streamwise vorticity. The experimental work is being conducted at the shear flow facility at United Technologies Research Center. During the past year, a set of experiments with lobed mixers has been designed and completed. The objective of the experiments was to assess the influence of the streamwise circulation generated by the lobed mixers, and of the convective Mach number, on mixing rate, mixing losses and radiated noise.

To make this assessment, the experiment was designed so that three independent parameters could be controlled: the streamwise circulation (Γ), convective Mach number (M_c), and velocity ratio (r). Streamwise circulation was controlled by tailoring the mixer lobe geometry. Four mixers were utilized with four different shed circulations. Convective Mach number and velocity ratio were controlled by varying the two stream Mach numbers. To isolate the dependence on M_c, the velocity ratio, r, was held constant while M_c was varied.

Diagnostics for the experiment included Mie scattering imaging from condensed ethanol droplets, Pitot surveys, wall static pressure measurements, acoustic measurements with flush-mounted wall microphones, fluorescent dye surface flow visualization, and Schlieren photographs.

The data obtained with these diagnostic tools is currently being analyzed. A contour plot of total pressure from a Pitot survey 2.3 wavelengths downstream of the most aggressive mixer (i.e. that with the highest shed streamwise circulation) is shown in Figure 7. Preliminary analysis of the data presented in the figure, as well as other recently obtained data, indicate that in high ($M_c >$ 0.6, say) convective Mach number flow regimes the mixing augmentation associated with the streamwise circulation is less than that observed in incompressible flow.

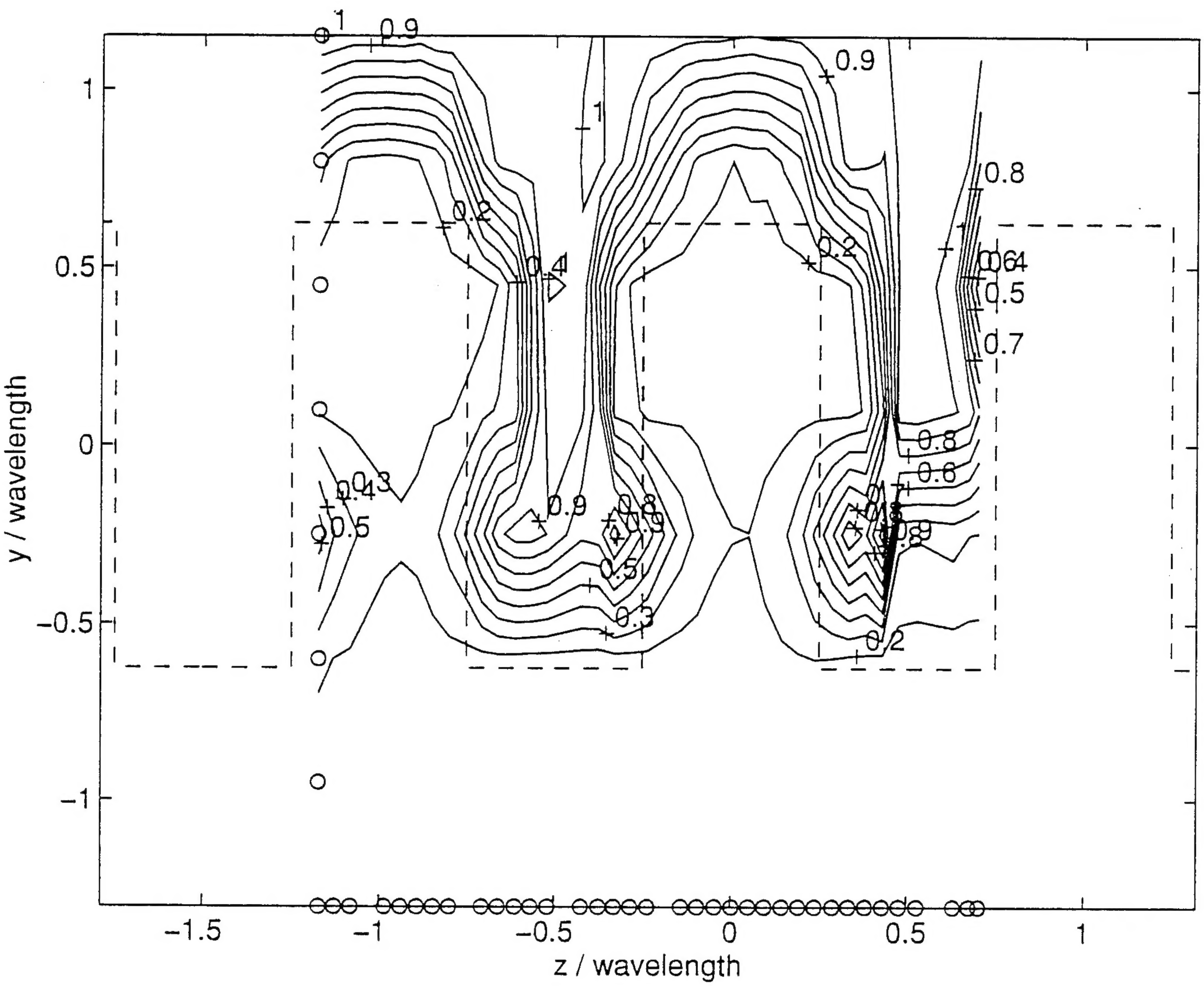

Fig. 7: Contours of total pressure / supersonic stream total pressure 2.3 wavelengths downstream of mixer ($\Gamma/\bar{U}\lambda = 1.2$). $M_c = 0.7$, velocity ratio = 0.3. [The vertical line of circles indicates vertical probe position, and the horizontal line of circles indicates horizontal probe position. The origin of the coordinate system is the geometric center of the tunnel.]